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INITIATION MECHANISMS OF SOLID ROCKET PROPELLANT DETONATION

by

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13. ABSTRACT

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COMPOSITE PROPELLANT IGNITION						
DOUBLE BASE PROPELLANT IGNITION						
NUMERICAL METHODS						

ABSTRACT

An experimental and analytical investigation was conducted to study the physical and chemical processes governing the ignition and release of energy under low amplitude, accidently applied stimuli. To determine the mechanisms responsible for initiation of detonation in low-speed impact a two-dimensional tensor code has been developed. The code is applied to calculations of the mechanical response of solid composite and double base propellant materials in unconfined impact against a rigid surface. Computations were also carried out for TNT to serve as a reference or baseline for comparison purposes. The materials were characterized by a hydrodynamic and by an elastic plastic-hydrodynamic equation of state. Estimates were made of the transient temperature field in these materials resulting from the dissipation of the mechanical energy of impact. Further, calculations indicated that the effect of friction at the interface was not a significant factor in producing high temperatures. The locus of maximum temperatures was found to migrate through the propellant cylinder. Initially the maximum temperature is attained near the outer edge of the target sample interface. This maximum value is maintained behind the shock front while sweeping across the cylinder toward the interior of the sample. When a second boundary is introduced, i.e., the material is at rest on a rigid base and is impacted by a rigid mass, the temperature developed almost doubles as a result of the reflections of the shock from the boundaries, compared with the case of the cylinder of material impinging on a rigid target.

Impact experiments on solid propellants and on inert simulants were carried out in support of the analysis. These propellants were a double base EJC/HMX/Al and two composite materials which were formulations of PBAN/AP/Al and PU/AP/Al. These experiments covered the range of impact velocities between that where no reaction occurs and that where transition to detonation occurs. Instrumentation consisted of framing camera photographs taken at 4 sec between frames so as to obtain early time details. Longer time phenomena were recorded by means of a fastax camera. The observed features of the deformation of the propellant are in good agreement with the analytical predictions.

1. INTRODUCTION

Weapons delivery systems in the future will require higher energy propellants and larger motors to improve performance. Higher energy systems have a tendency to be impact sensitive. Impact is the most common occurring accident situation.

The answer to many questions concerning the hazards associated with solid rocket motors are not known, and where doubt exists, they must be resolved in the favor of a more conservative safety criteria. With the advent of even larger solid motors, the cost of "more safety" has become prohibitive. Therefore, it is necessary to accurately analyze and predict the hazards and damage capabilities of solid propellants and to understand the processes which govern the hazardous energy release. A knowledge of the various mechanisms by which propellants react when they are subjected to stimuli of moderate amplitude will lead to the establishment of criteria for the formulation of less sensitive propellants

The existing detonation theories describe the steady-state detonation of propellants and explosives by strong shock waves reasonably well. However, detonation of propellants and explosives can occur under low-amplitude shocks and by impact at impact speeds and pressures that are well below those predicted by hydrodynamic theory of detonation. Equally as important as high-order detonations is the class of chemical decompositions referred to as subdetonation reactions. Such reactions occur when the stimulus is not sufficient to cause high-order detonation but is sufficient to cause disturbances with intensity levels ranging from mild burning to low-order detonation. Subdetonation reactions occur at relatively low pressures; hence, they are of interest in determining the potential hazards of propellants to accidental stimuli such as impact or mechanical action, the most commonly occurring accidental situation.

Large deformations characterize the mechanical response of solid propellant materials prior to initiation in realistic accidental impact situations and in low-velocity unconfined impact experiments. To determine the mechanisms responsible for propellant ignition in low-speed impact requires an understanding of material flow and energy conversion processes in unconfined dynamic compression. To achieve this objective combined theoretical-experimental investigation was carried out. Analytical studies can reveal parameters whose role or significance is masked in interpretations of experimental results, since the complexity of the phenomena do not readily lend themselves to experimental observation. Insight into hazardous conditions not tested in the laboratory may also be revealed by an analytical model. A knowledge of mechanisms governing the initiation process and their relationship to the physical properties of propellants can provide guidelines for the formulation of less sensitive propellants with reduced damage capabilities while maintaining their necessary performance and ignition characteristics. The data obtained on initiation mechanisms will result in the development of large solid propellant motors of reduced sensitivity with a subsequent increase in personal safety and better utilization of resources.

2. SENSITIVITY EXPERIMENTS ON SOLID PROPELLANTS

Accidents involving solid propellants rocket motors, such as the destruction of an inflight motor as a result of a malfunction at launch, have resulted in considerable damage to the surrounding area. The effects to the surrounding are similar to that of a detonation of a high explosive. In the laboratory however, when these propellants are subjected to a high pressure-short duration load from a detonating high explosive donor, as in the gap test, the most commonly used sensitivity test, the propellant cannot be ignited and it generally shatters. On the other hand initiation of burning and detonation reactions occur at a much lower pressure by the long duration loads occurring as a result of low-speed impact.

Flyer plate impact experiments Figure 1, on solid propellant materials and their inert mechanical simulants were carried out in order to determine deformation modes, impact speed required for initiation, intensity of the reaction, assist in the development of the theoretical model, and to substantiate the predictions of the analysis. The Beckman & Whitley model 189 framing camera, operating at a framing rate of four microseconds between frames, was used to observe the deformation of the propellant during the early times, the first 100 μsec. Fastax cameras operating at 5000 fps were used for late time phenomena. Details of the experimental setup can be found in Ref. 1. The experiments were conducted on two composite solid propellants, similar in composition except for binder, and one double base propellant. Their corresponding inert mechanical simulant was also tested at the same loading condition. The two composite propellants (PBAN and ANP) had aluminum as the fuel and ammonium perchlorate as the oxidizer. The binder materials were PBAN and polyurethane, respectively. The double base propellant consisted of aluminum as the fuel, HMX as oxidizer and EJC as binder. Experiments were carried out on EJC, PBAN and ANP to bracket the ignition threshold and intense reaction region. Each of the propellants

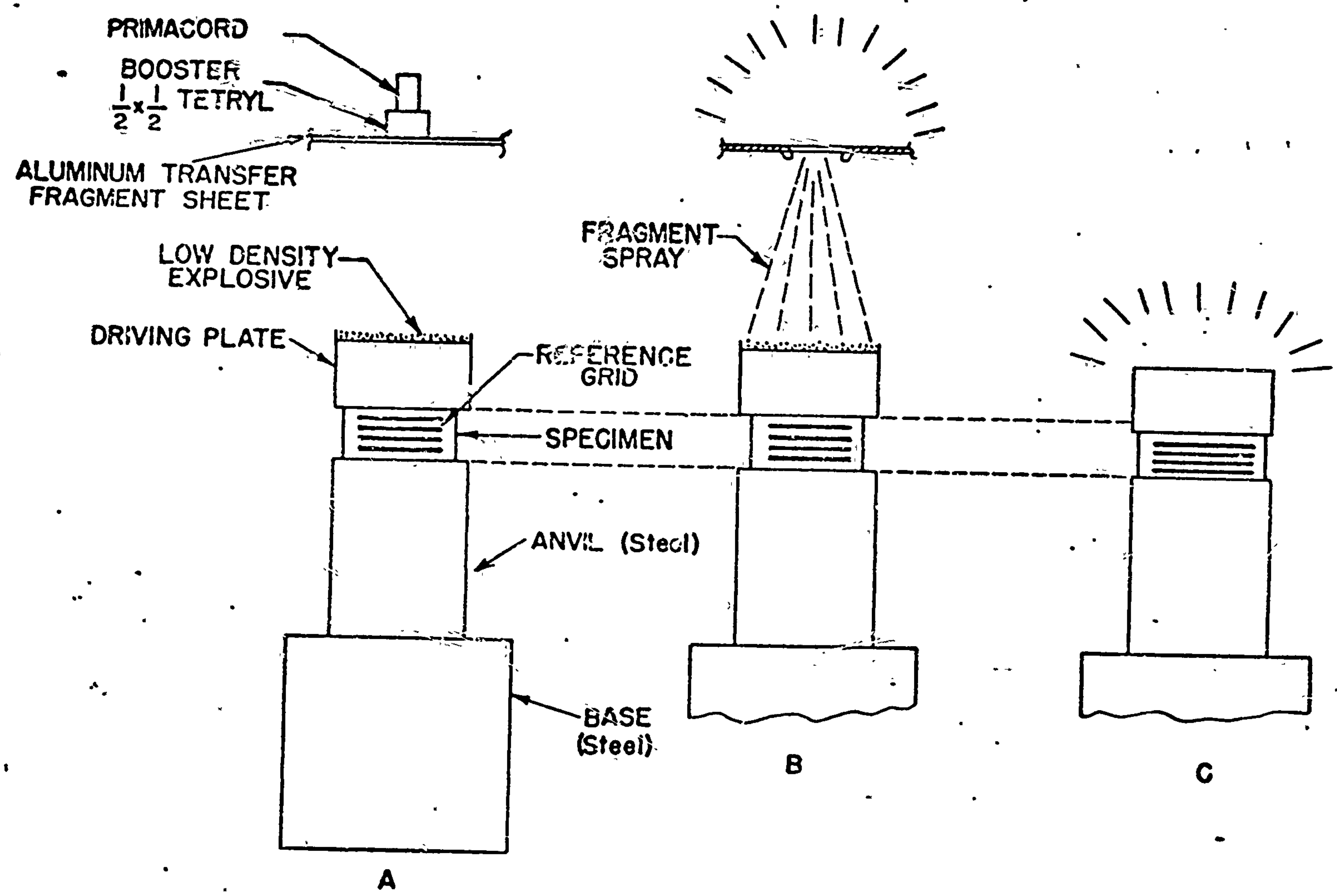


Figure 1 Test Arrangement

were impacted at speeds ranging from 200 fps to 800 fps. The samples were cylindrical in shape, 5 in. diameter by 5 in. high. The results of these tests are summarized in Table 1. Tests on an inert simulant, HDLK, carried out at the same impact speeds resulted in recovery of the compressed and fractured material.

One of the important observations made is that composite and double base propellants can exhibit intense reactions, resembling low-velocity detonation, at impact speeds of ~ 800 fps. These materials were considered to be insensitive by other tests. The dimensions of these materials were well below their critical diameter for detonation, which was determined to be of the order of 60 in. for PBAN.(2)

Other experiments were carried out to determine the ignition threshold as a function of charge size for PBAN solid propellant. Sample sizes ranged from 1 in. to 10 in. in length and 4 to 10 in. in diameter. It was found that the PBAN propellant is exceedingly easy to ignite by impact, requiring a plate impact speed of 150 to 300 fps, depending on charge size. However, the intensity of the reaction at these impact speeds in a mild burning. Even at higher impact speeds, reactions of the PBAN propellant were less intense than those observed for the polyurethane propellant.

If the term "sensitiveness" denotes the ease with which a material is ignited by a given stimulus, and "explosiveness" denotes the intensity of reaction of the material when ignited, then in these terms, PBAN is the more sensitive material but ANP is more explosive. Although materials may be characterized by these terms, we do not yet know which physical or chemical properties govern the sensitiveness and explosiveness of a material to a given input stimulus.

It was also observed in Fastax film records that the ANP propellants, in particular, produced firebrands. This is, upon impact the material fragmented into a large number of burning pieces. These pieces of lit propellant, firebrands, travelled

Table 1

SUMMARY OF IMPACT EXPERIMENTS ON SOLID PROPELLANTS

IMPACT VELOCITY (fps)	PROPELLANT		
	EJC HMX/EJC/AL	PBAN AP/PBAN/AL	ANP AP/PU/Al
200	No Go	No Go	No Go
300	Scattered Burning	Partial Burn, Fragments	Partial Burn, Fragments
600	Burn In Place	Burn In Place	Partial Burn, Firebrands
800	Bowed Plate, Metal Flow	Burn In Place	Bowed Plate, Metal Flow

hundreds of feet. Thus there is not only the blast or overpressure hazard but also the fire hazard associated with low speed impact. EJC on the other hand did not produce firebrands. It is the intent of the analytical work described in the next section to provide a detailed understanding of the impact and material flow processes to determine the way in which the mechanical energy is converted to thermal energy, and to determine the effects of material properties on this conversion process.

3. COMPUTATIONAL EFFORT

This work consists of the numerical modeling of the flow phenomena occurring in material billets subjected to impact. The primary purpose is to determine regions within the material which may serve as initiation sources due to generation of local high temperatures.

Calculations were performed with a two-dimensional unsteady computer code described in Reference 3. Additional details of the numerical technique are reported in Reference 4. The materials considered were both propellants and explosives. The latter were included for comparison purposes and also because more information regarding their behavior, properties, and equation of state data is available. Early in the development of the computer code checkout calculations were performed using aluminum. Both purely hydrodynamic and elastic-plastic modeling of the materials were used. The early computations were performed in order to analyze the deformation of the impacted material and to study the wave and flow patterns generated by the impact. Later the capability to compute local temperatures for a particular form of the equation of state was added (see Reference 3). Most modeling was done for unconfined impact in which a cylindrical billet of material is impacted on a rigid surface which is perpendicular to the cylinders axis. Both cases with and without friction on the impact surface were computed. Finally results were obtained for impact of a flyer plate on a cylindrical billet which in turn rests on a rigid surface. This latter configuration is the one used in most impact sensitivity tests on explosives and propellants (see Reference 1).

A tabulation of the significant computer runs performed during the duration of this program is presented in Table II. This table indicates the impact conditions, the type of material, and the material behavior specified. Also listed is the purpose of the computation. Some of the detailed results obtained for

TABLE II. SUMMARY OF COMPUTER RUNS

Material Type	Material Behavior	Impact Condition	Remarks
PBAN	Hydrodynamic	Unconfined	No Temperature was computed - Study of wave motions
EJC	Hydrodynamic	Unconfined	Temperature Distribution Computed
TNT	Hydrodynamic	Unconfined	Temperature Distribution Computed
TNT	Hydrodynamic	Unconfined	Friction at Rigid Boundary - Temperature Computed
TNT	Elastic-Plastic	Unconfined	Temperature Distribution Computed
TNT	Elastic-Plastic	Unconfined	Friction at Rigid Boundary - Temperature Computed
TNT	Elastic-Plastic	Flyer Plate (1570 gm)	Temperature Distribution Computed
TNT	Elastic-Plastic	Flyer Plate (1570 gm)	Influence of Grid Resolution on Temperature Values (10 x 10 zones)

the free impact calculations are presented in Reference 3. Additional results for this case and also the results for the flyer plate impact computation are given in Section 4.

To minimize the complexity of the computational results and to be able to make valid comparisons between the behavior of various materials and impact conditions the billet geometry was standardized to be a cylinder with a height of 5 cm and a radius of 5 cm. Also the numerical resolution for most runs was the same, 30 radial zones and 30 axial zones. Finally the impact velocity in all cases was assumed to be 21 cm/msec ($\sim$700 ft/sec). All computations except the run using PBAN were performed using the equation of state formulation given in Reference 3.

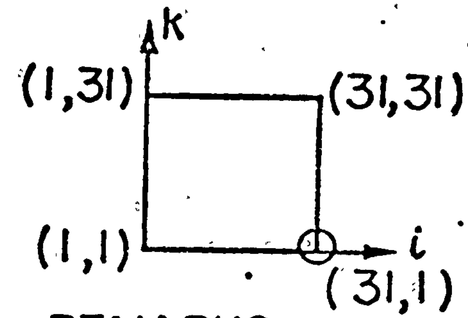
The caloric equation of state used for PBAN relates pressure p, density ρ, and internal energy e as follows:

$$p = A_1 \rho e + B_0 + B_1 \rho + B_2 \rho^2 + B_3 \rho^3 .$$

4. NUMERICAL RESULTS

The sequence of dynamic events in a cylindrical billet in normal unconfined impact on a rigid surface is illustrated in Figure 2. The specific results shown are for a PBAN propellant and hydrodynamic behavior of the material is assumed. The impact generates a shock wave moving upwards from the rigid interface. However, since the lateral surface of the cylinder is free rarefaction waves move in to relieve the pressure as indicated in the Figure. The flow field behind the original shock is simply one-dimensional. Once the rarefaction wave moves in, the flow field becomes two-dimensional. After sweeping through the entire billet the shock encounters the top free surface reflecting a strong rarefaction down into the material. This wave interacts with the rarefaction waves coming in from the lateral boundary setting up a complex wave pattern in the billet. Further interaction of these waves with the rigid and free boundaries take place. In general these tend to relieve the pressure. Finally regions of strong tension may appear in the material particularly along the centerline. Figures 3 and 4 illustrate the pressure field for the PBAN calculations at two times. Also shown are displacements and distortions which occur in the material due to the impact. As should be expected the largest lateral displacements occur along the rigid boundary.

The behavior of other materials in unconfined impact is qualitatively the same as described above. This is illustrated in Figure 5 which shows the displacements and temperatures for impact on an EJC billet. Similar results for TNT are contained in Reference 3. A comparison of the mechanical behavior of the three materials is shown in Figure 6. For all cases hydrodynamic behavior is assumed. Shown are the velocities and displacements at the corner of the billet. Again the similarity in behavior may be observed. Largest displacements and velocities are obtained for TNT. In general displacements and velocities in



HIGHLIGHTS OF COMPUTATION

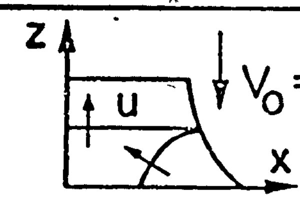
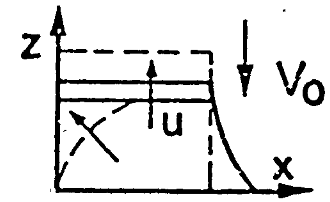
CYCLE NO.	TIME (μsec)	LOCATION OF SHOCK	LOCATION OF HEAD OF RAREFACTION	REMARKS
70	11.94	k = 14 (Halfway)	i = 16, k = 1	 V_o = 21 cm/msec
170	22.74	k = 26	i = 1, k = 1	 V_o
210	26.20	k = 30 Top Surface		Velocity at k = 31 = 0
230	27.81	Last Cycle at Which 1-D State Exists P = 7.1 kb, at k = 1, k = 23		Free Surface Velocity = + 23 cm/msec
240	28.60	1-D Region Has Vanished Peak Pressure = 6.9 kbar		
300	33.03	Peak Pressure = 0.8 kbar (~10% of Impact Pressure)		

Figure 2. DYNAMIC SEQUENCE IN UNCONFINED IMPACT

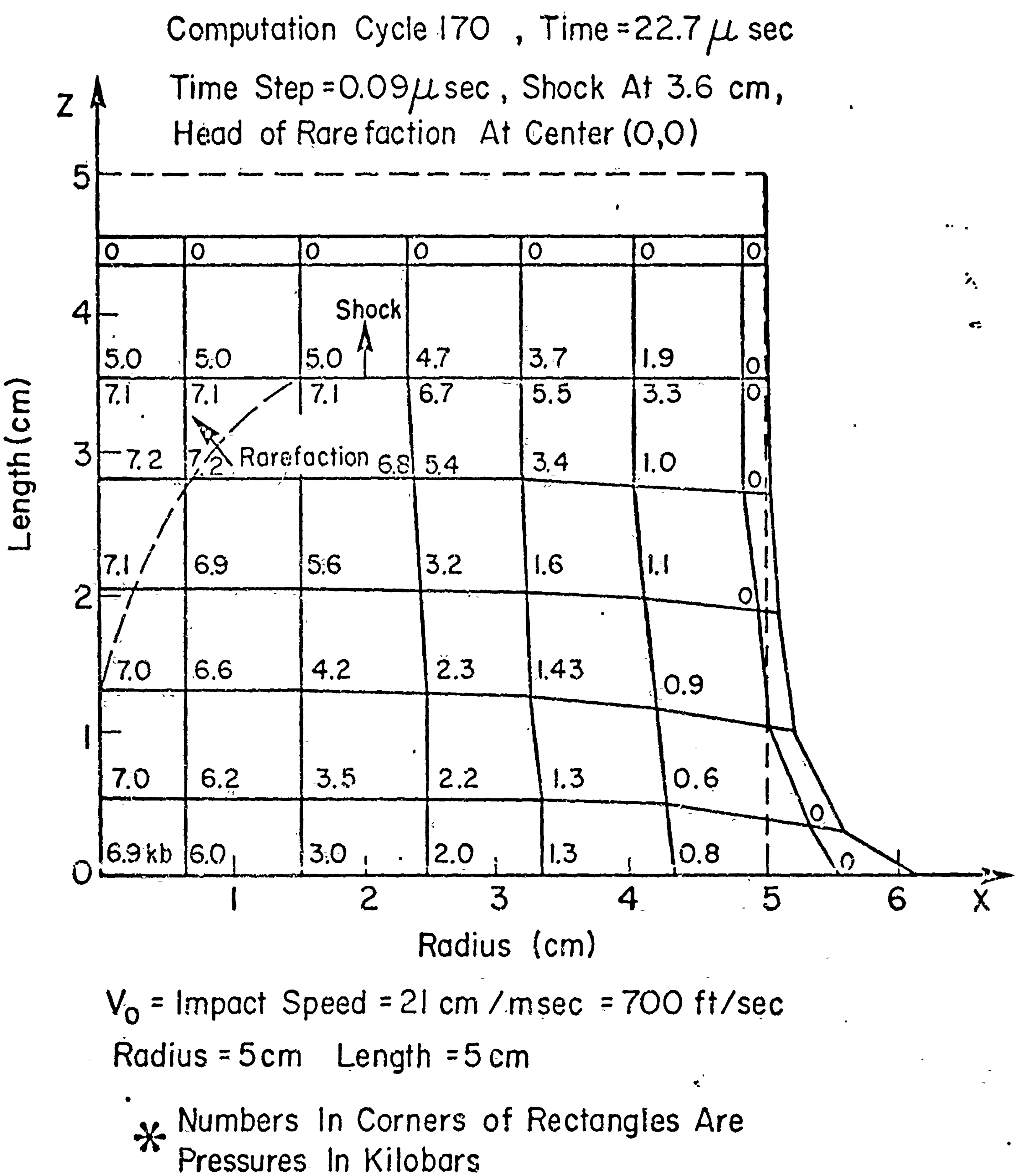


Figure 3. PRESSURE AND DISPLACEMENT FIELD IN UNCONFINED IMPACT - PBAN (Hydrodynamic)

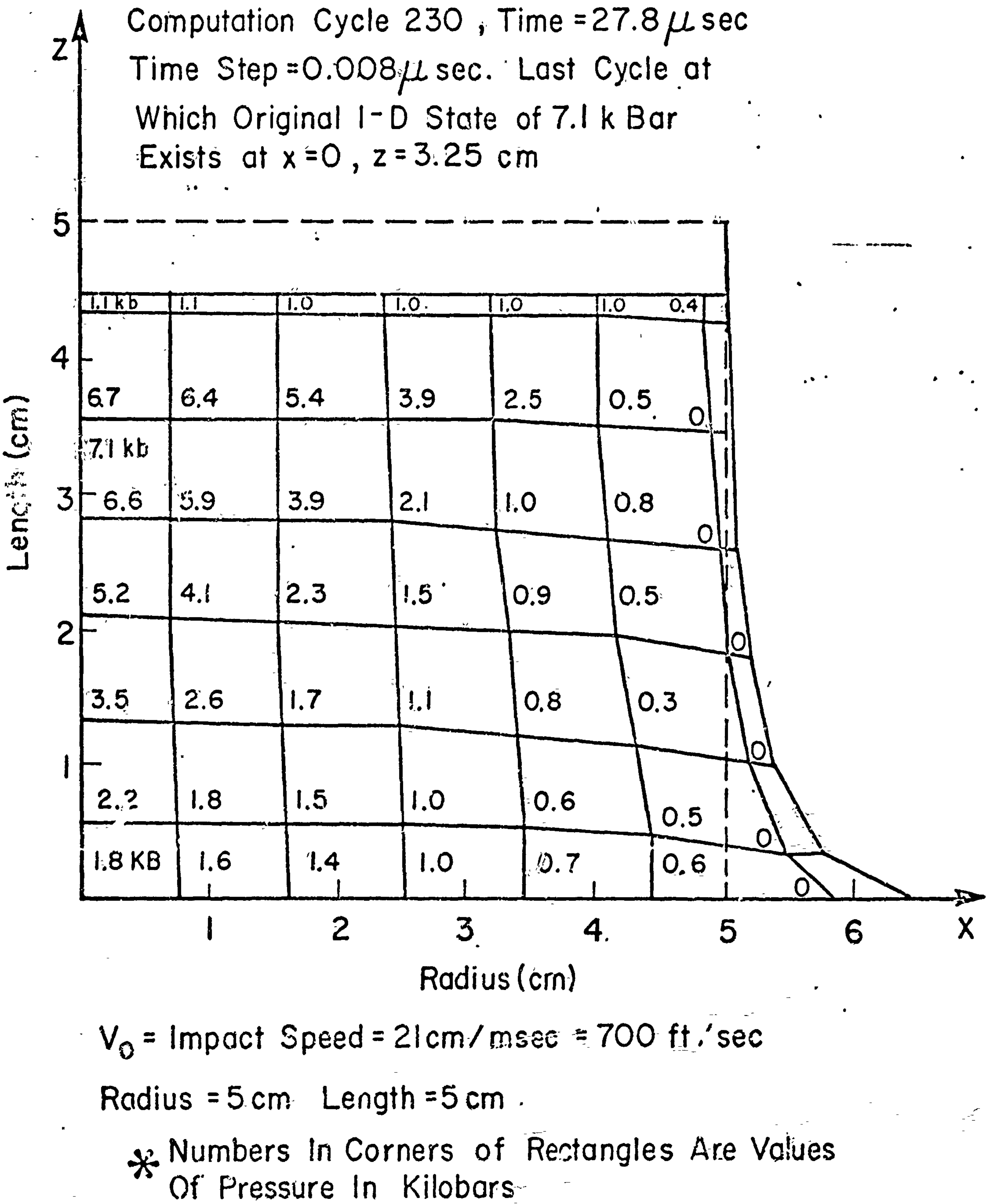
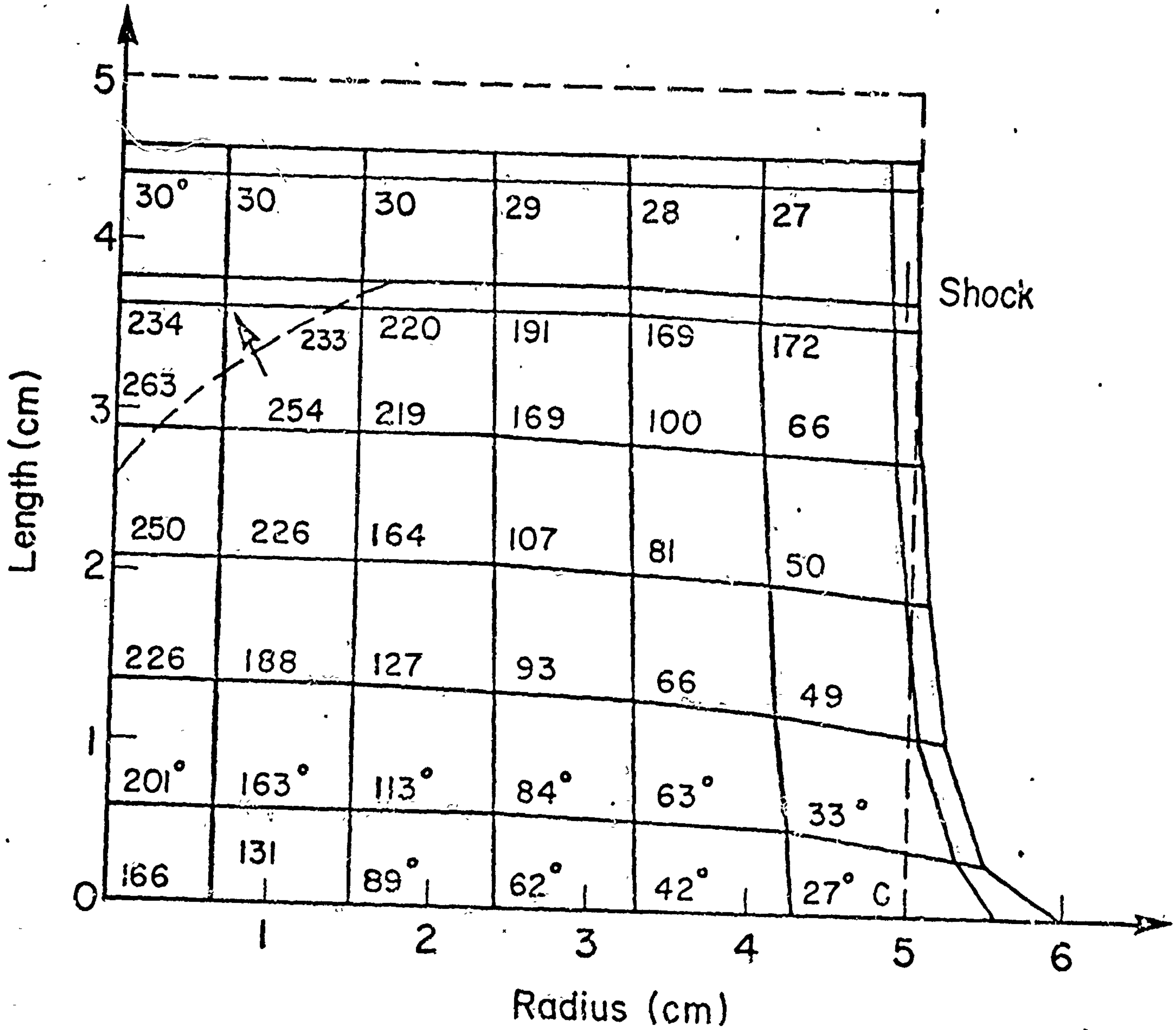


Figure 4. PRESSURE AND DISPLACEMENT FIELD IN UNCONFINED IMPACT - PBAN (Hydrodynamic)



Impact Speed 21cm/msec Time = 20.6 μ sec

Shock At 3.75 cm Head Of Rarefaction at (0, 2.6 cm)

Initial Radius and Length 5 cm X 5 cm

* Numbers In Corners Represent Temperature In °Centigrade

Figure 5. DISPLACEMENT AND TEMPERATURE FIELD IN UNCONFINED IMPACT - EJC (Hydrodynamic)

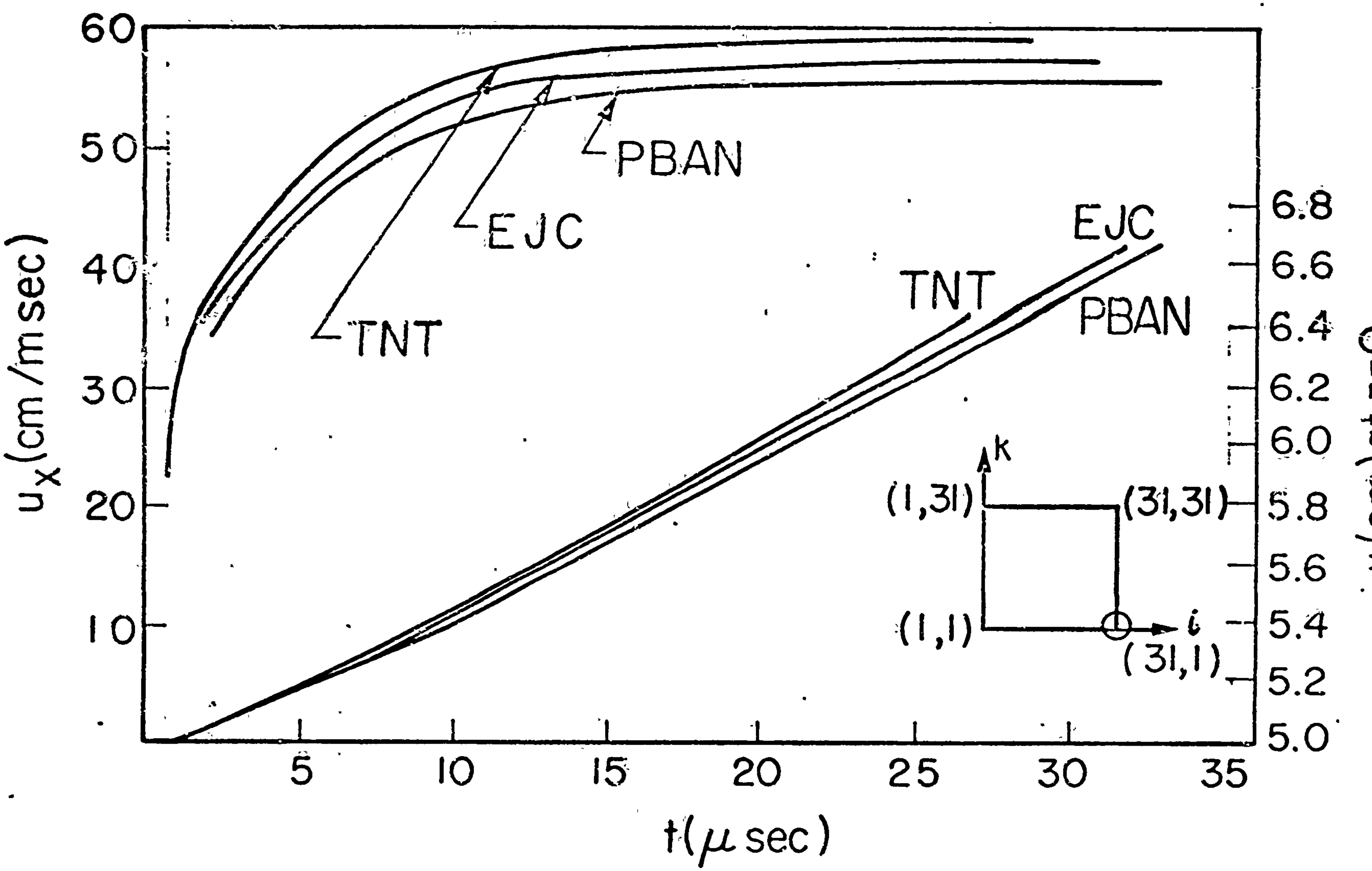


Figure 6. VELOCITY AND DISPLACEMENT VS. TIME AT CORNER OF BILLET i = 31, k = 1, EFFECT OF MATERIAL TYPE

the hydrodynamic approximation are primarily a function of the density, i.e., less dense materials are accelerated to higher velocities and attain larger displacements in the same time. This is clearly borne out by the results of Figure 6. To ascertain the influence of material strength on the mechanical behavior, impact calculations were performed for TNT assuming elastic-perfectly plastic behavior. A yield strength of 1.21 kilobars was specified. The effect of material strength is clearly demonstrated in Figure 7 which again shows the corner displacement and velocity. Both the velocity and the displacements are considerably reduced when material strength is taken into account.

Since the purpose of this study is to delineate possible initiation mechanisms for propellant and explosive materials the most significant computational results are the temperature distributions. Typical of the calculated temperature fields is the one for EJC shown in Figure 5. The highest temperatures in unconfined impact occur generally behind the propagating shock wave. The location of the maximum temperature for the EJC impact is shown in Figure 8. Similar results for TNT are given in Reference 3. It may be seen that the maximum temperature never occurs at locations close to the free surfaces. The location of maximum temperature approximately follows the shock path upwards through the billet. The effect of material type on the temperature is illustrated in Figure 9. Maximum temperature as a function of time is given for TNT and EJC. The latter material exhibits higher temperatures which is a reflection of the lower specific heat. Figure 10 shows the effect of taking into account the strength of a material on the temperature field. As should be expected higher temperatures prevail when a purely hydrodynamic behavior is assumed. The pressures in the hydrodynamic material are also higher. When material strength is included part of the impact energy is dissipated in distorting the material, i.e., in mechanical work.

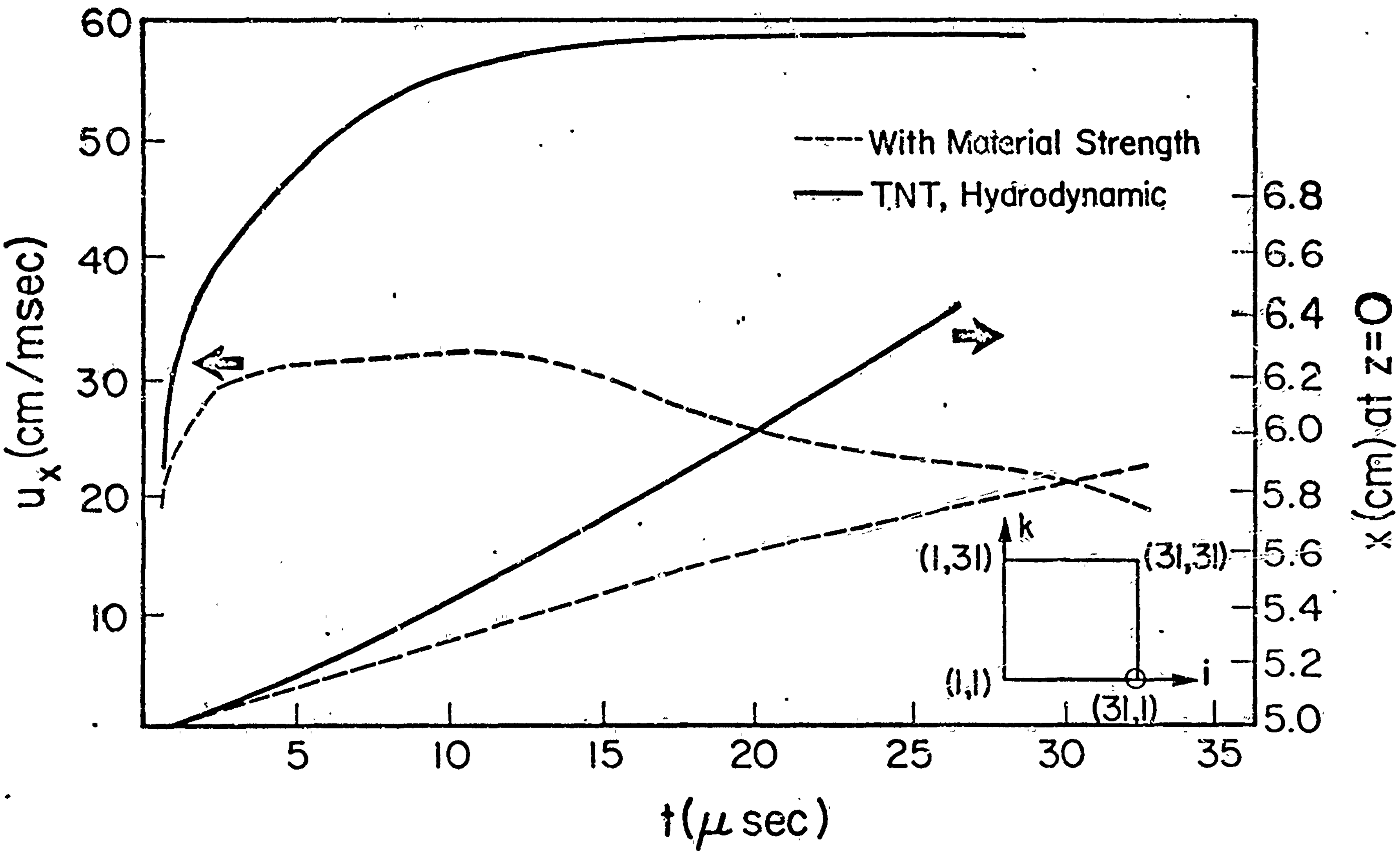


Figure 7. VELOCITY AND DISPLACEMENT VS. TIME AT CORNER OF BILLET, i = 31, k = 1, EFFECT OF MATERIAL STRENGTH

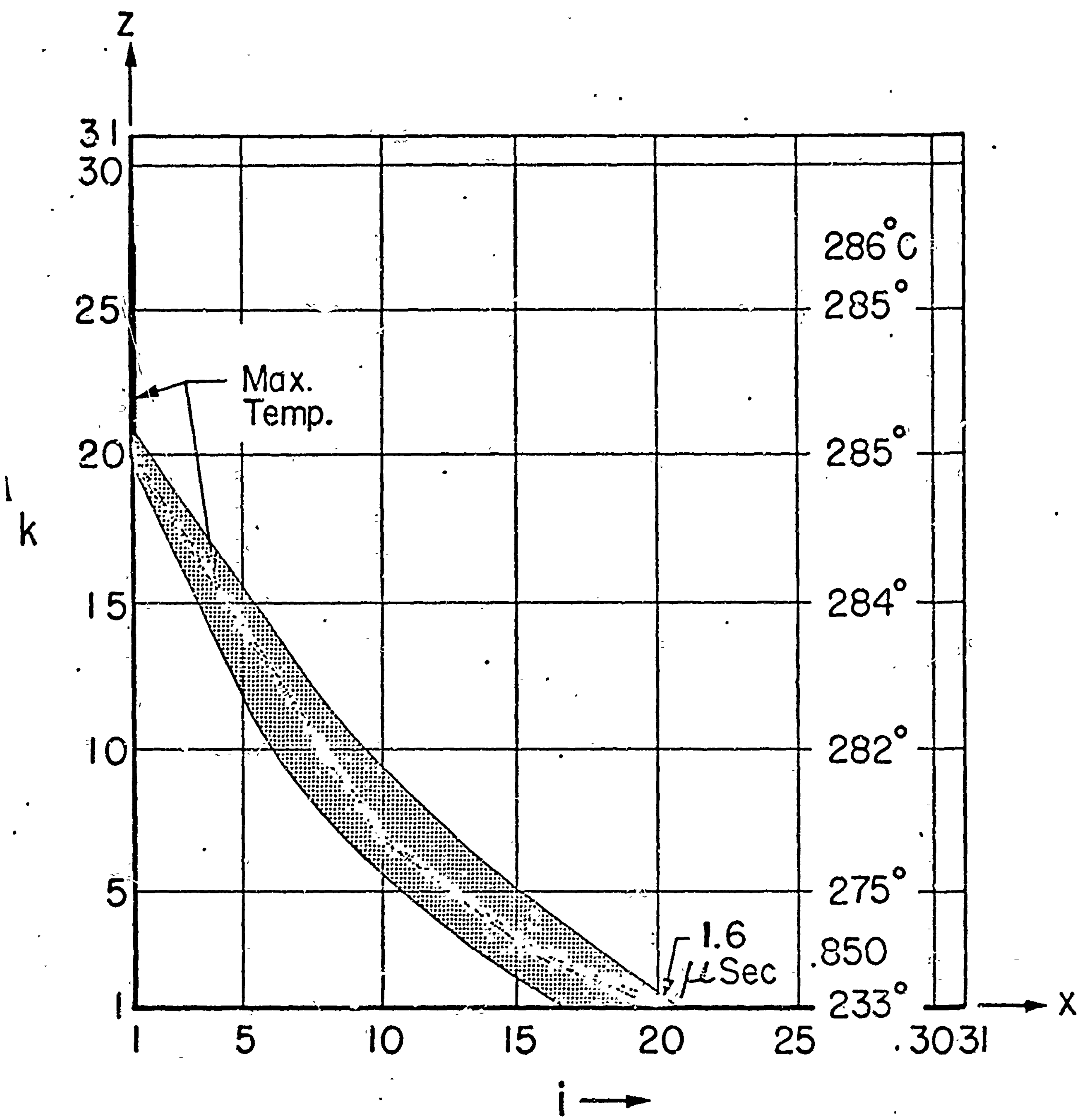


Figure 8. EJC - LOCATION OF MAX. TEMPERATURE SHOWING SPREAD

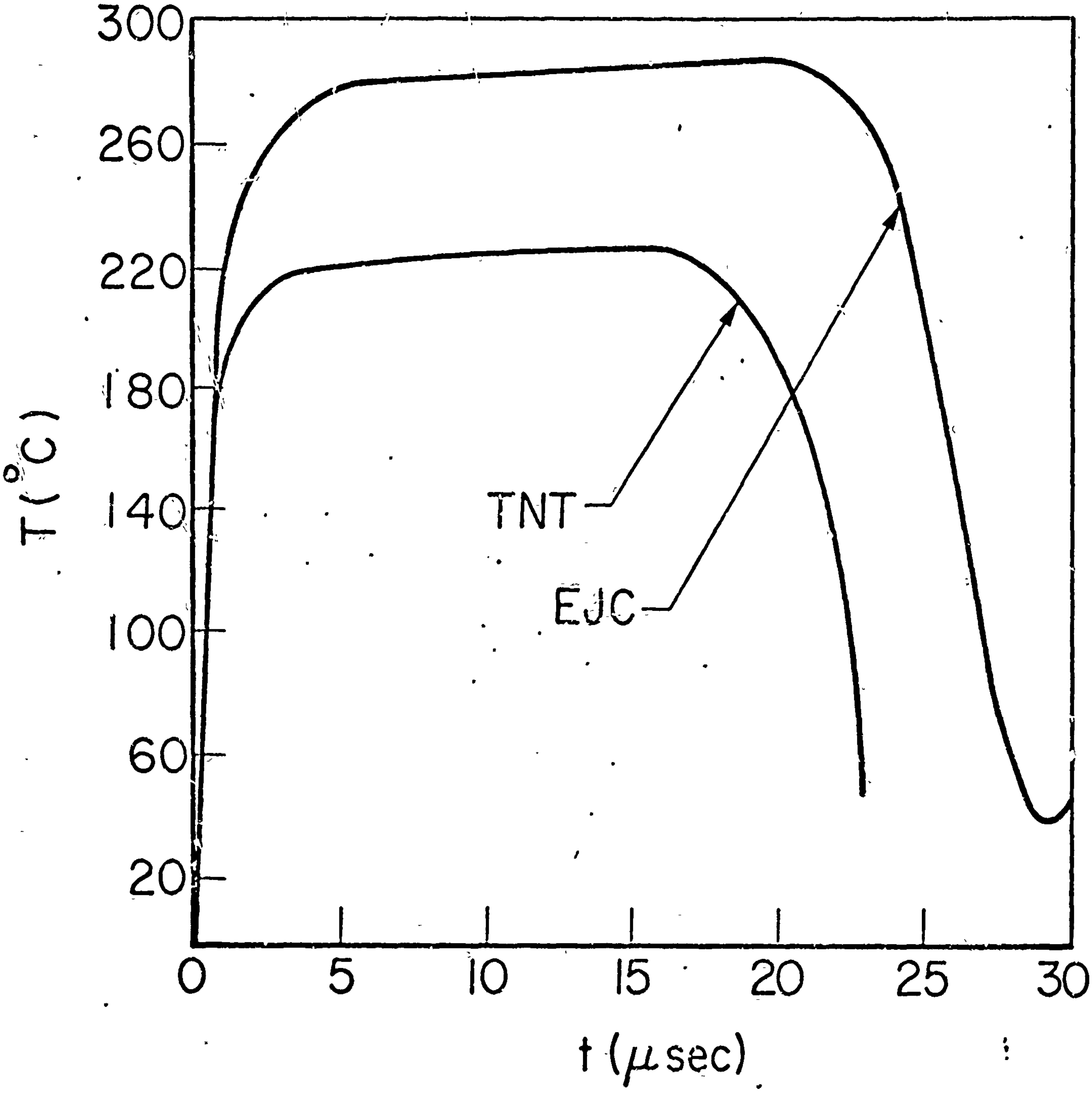


Figure 9. MAX. TEMPERATURE VS. TIME V_o=21 cm/msec
EFFECT OF MATERIAL TYPE

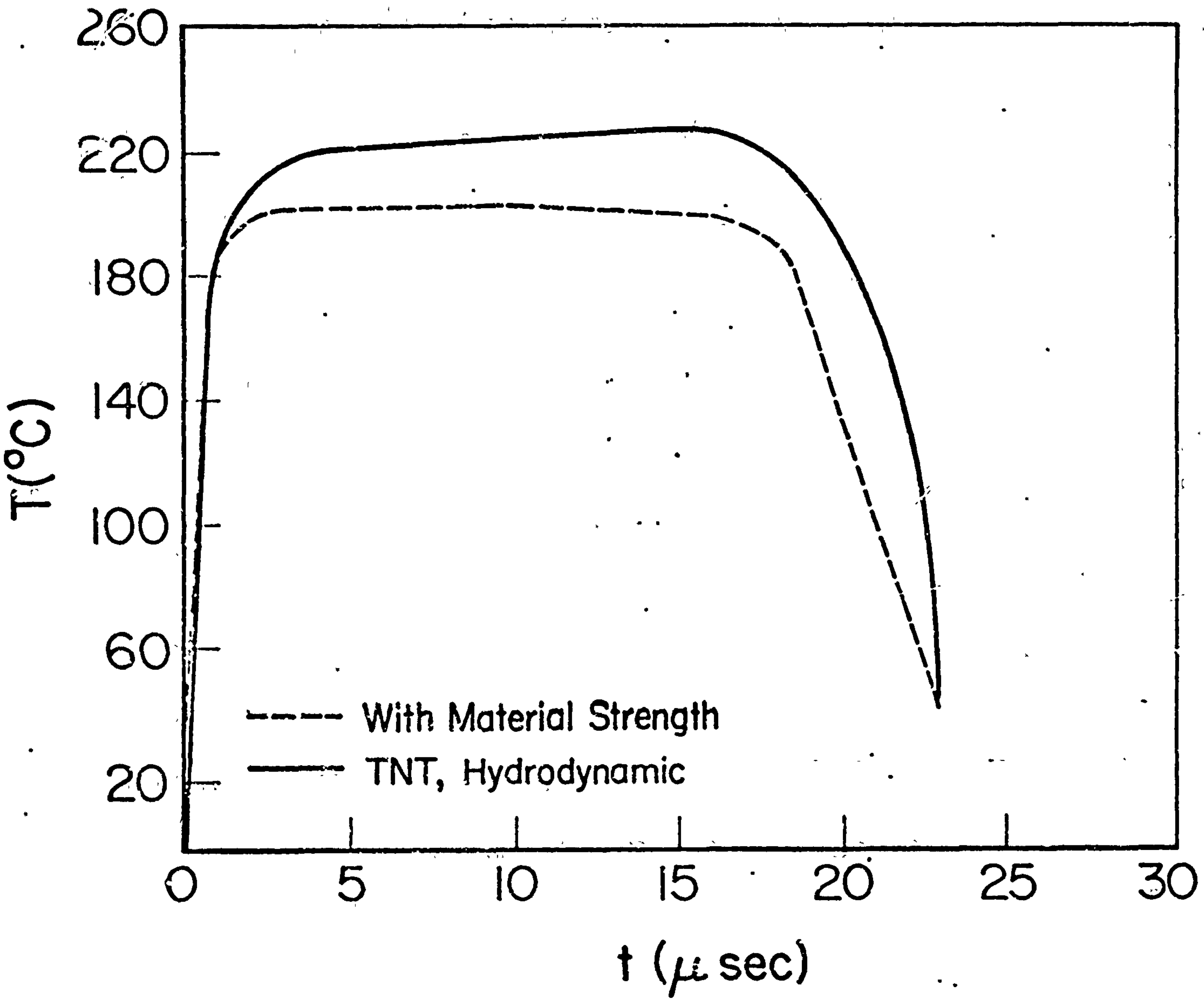


Figure 10. MAX. TEMPERATURE VS. TIME V_o = 21 cm/msec EFFECT OF MATERIAL STRENGTH

To determine the significance of surface friction in unconfined impact, computations were performed including the friction effect at the rigid surface. These calculations were made for TNT both with and without material strength. It was found that the effect of friction on the temperature increase was minimal. More significant was a slight reduction of the radial velocity and displacement along the rigid surface. It is possible that a very local temperature increase may occur at the surface but cannot be resolved without introducing a much finer computational grid in this region. Thus the problem of friction may require additional study.

Since the computed temperatures in unconfined impact were found to be quite moderate calculations were performed for partially confined impact. The same size billet was used but now resting on a rigid surface, and being impacted by a rigid flyer plate from above. The impacting plate was assumed to have a mass of 1570 gm and the same initial velocity as the free impacting billet. Considerable higher temperatures were now computed, this is shown in Figure 11 which compares the maximum temperatures as a function of time for the plate impact case with the unconfined impact. Identical material properties were assumed for both cases. The particular computation is for TNT with material strength. Also shown in this figure are results for plate impact obtained with a coarser computational grid (10 zones in each direction rather than 30). The temperature predicted is seen to be lower. This indicates that a coarse computational grid is not capable of sufficiently resolving the flow field to determine the maximum temperatures since these are normally restricted to a small region. The location of the maximum temperatures for the plate impact case is indicated in Figure 12. Again the maximum occurs on the interior of the billet close to the centerline.

Finally to study the distortion occurring in such a billet a graphical capability was developed which permits the CALCOMP

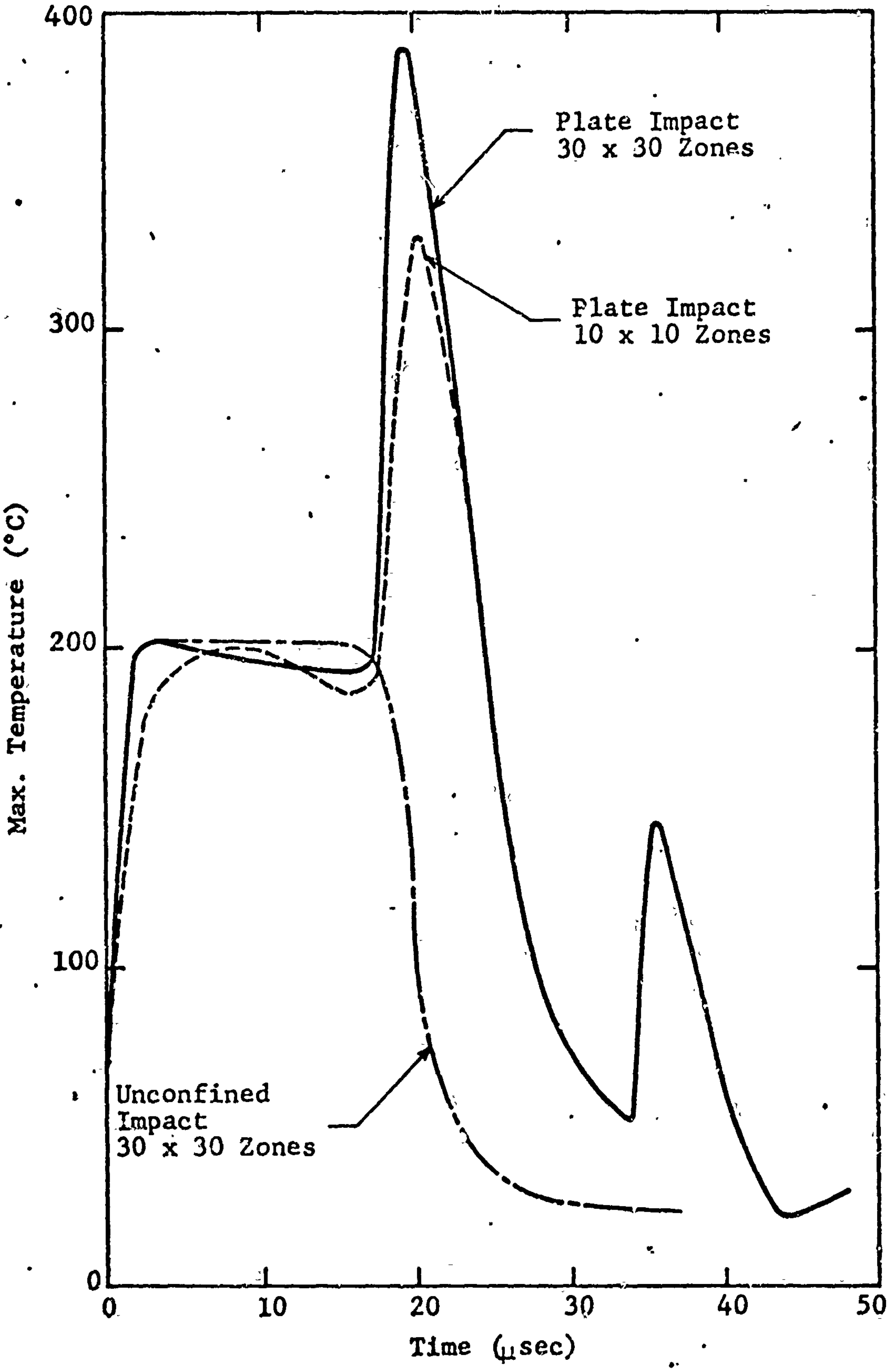


Figure 11. Max. Temperature vs Time for TNT Elastic-Plastic Material Behavior

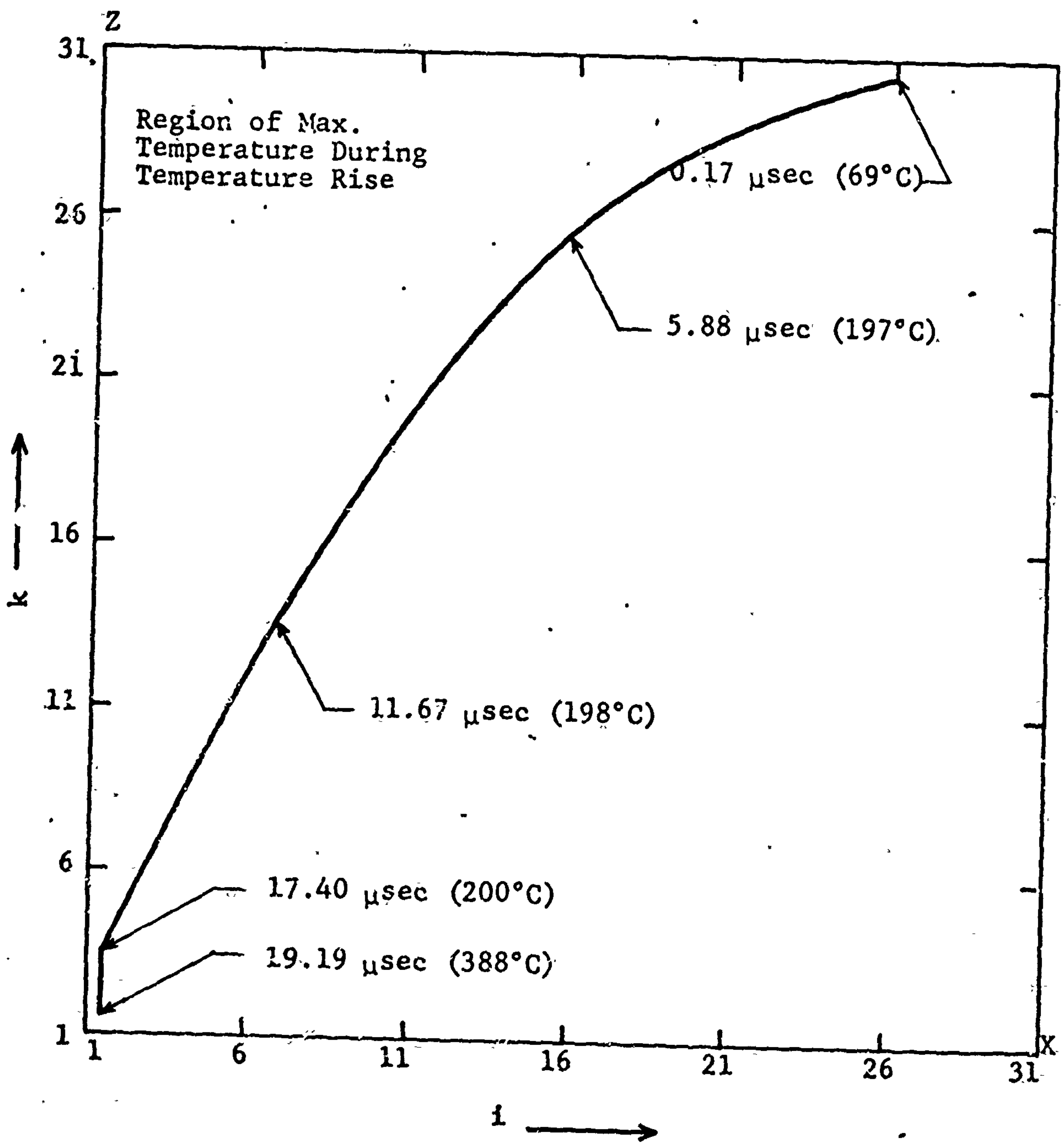


Figure 12. LOCATION OF MAX. TEMPERATURE FOR TNT PLATE IMPACT PROBLEM

plotting of the grid network. Figure 13 shows a typical sequence of such plots starting with the initial rectangular grid and proceeding with consecutive time plots. These plots are full scale and show the same behavior as observed in experimental studies (see Reference 1).

The much higher temperatures obtained with the plate impact indicate that it may be possible to initiate explosives and propellants under these conditions of partial confinement. Additional confinement may raise the local temperatures still higher. Hence this problem deserves further attention. Other effects that should be analyzed are the geometry of the material, the presence of voids, and the encasement of the propellant in metal housings. These studies can be readily accomplished with but minor modifications of the existing code.

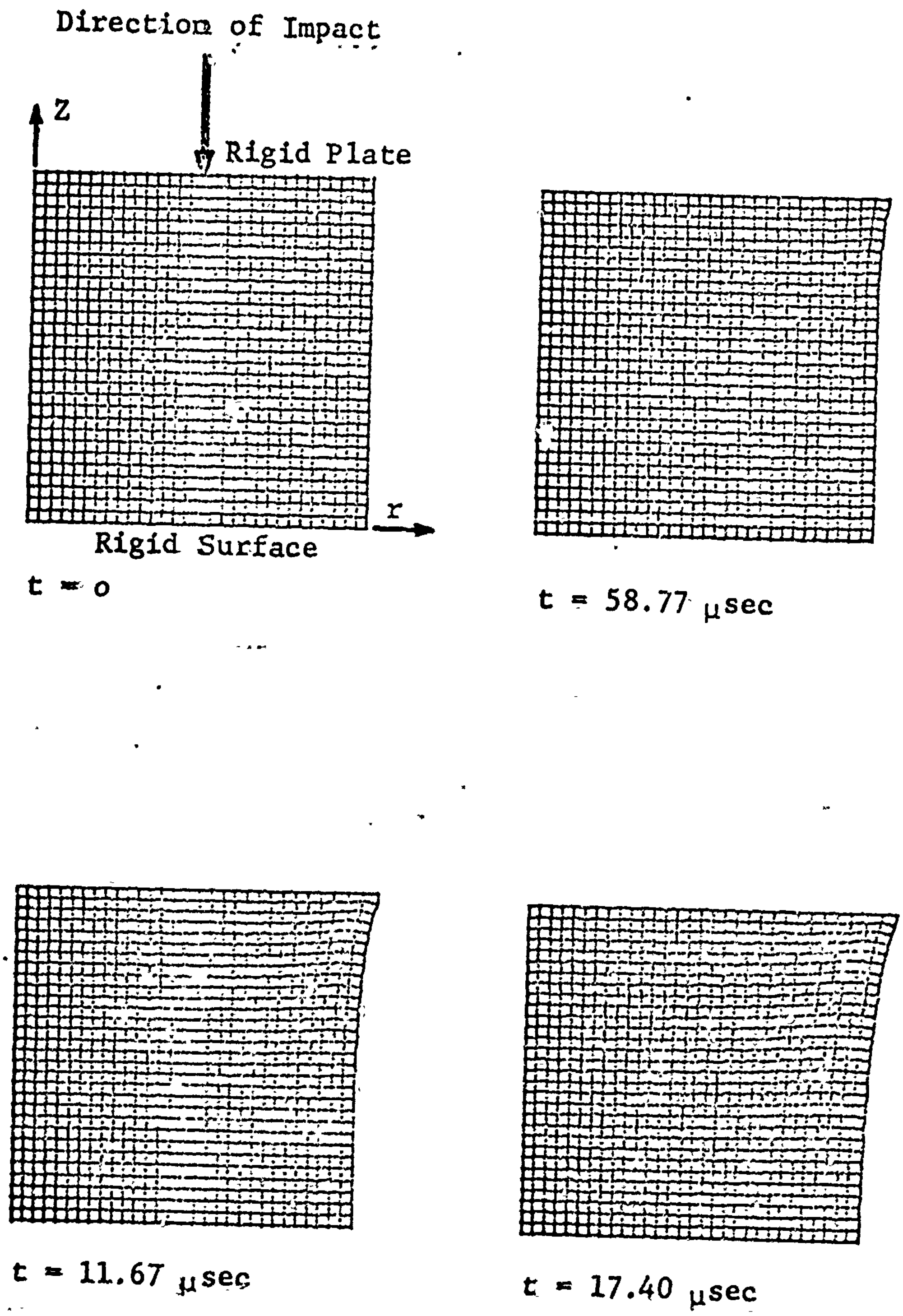
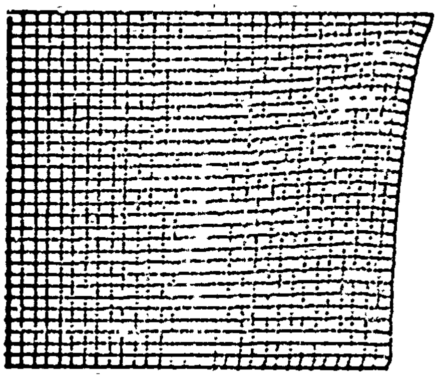
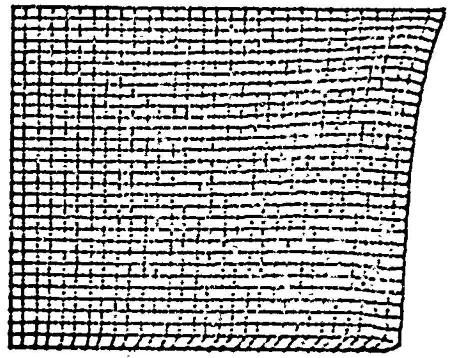


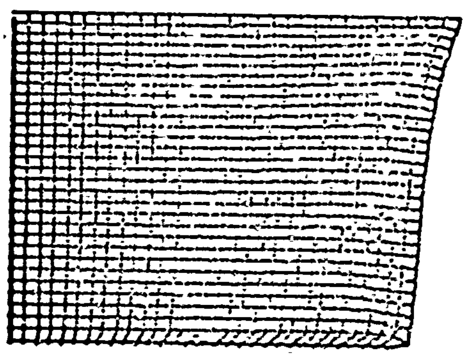
Figure 13a Deformation of TNT Billet During Plate Impact V_o = 21 cm/msec



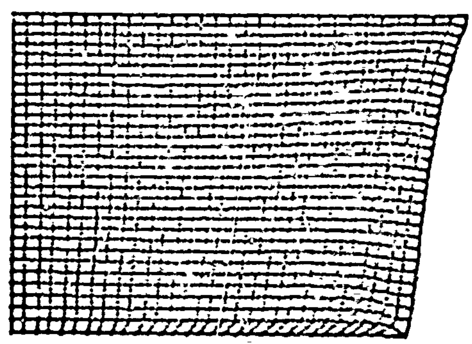
t = 22.52 μsec



t = 32.11 μsec



t = 39.82 μsec



t = 47.01 μsec

Figure 13b Deformation of TNT Billet During Plate Impact V_o = 21 cm/msec

5. CONCLUSIONS

The results of this investigation have shown that explosive reactions can occur for composite and double base propellants under conditions of laterally unconfined low-speed impact by a rigid flyer plate. The mathematical model of the impact process shows that there is an almost two-fold increase in temperature, under conditions of flyer plate impact, with the propellant resting on a rigid target, compared with the case of the propellant impinging on the rigid target. The maximum temperature achieved, ~400°C, is sufficiently high to cause chemical reaction. In addition numerical tests using different computational mesh sizes showed that higher temperatures are achieved using finer meshes, indicating that the development of high temperatures is a very local phenomena. For low-speed impact the total applied energy is never sufficient to cause a rise in temperature of more than a few degrees throughout the bulk of the material. Hence it has been recognized that in order to effect an explosion the energy must be concentrated in a small region of the material. In our computations we see that this region is a sphere about 0.08 cm radius which achieves a temperature of ~400°C. Bowdene (5) has calculated hot-spot radii for explosion of 10^{-3} to 10^{-5}cm with temperatures ranging from 400° to 600°C depending upon the explosive.

These observations indicate that the hot spot theory cannot be supported unambiguously. There are other mechanism for concentrating energy (6) which are dependent upon geometry, composition, and details of the applied load. In our application elastic-plastic changes behind the shock front with localized shear or fracture appear to be the dominant mechanism.

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